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Urban transport carbon dioxide (CO_2) emissions by commuters in rapidly developing Cities: The comparative study of Beijing and Xi'an in China

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ABSTRACT

To understand the changing relationships between commuting CO_2 emissions (CCE), travel behavior and urban forms, this paper provides a comparative study between the typical Chinese cities of Beijing (more developed) and Xi'an (rapidly developing). Further, the effects of metro services on reducing CCE were explored, and comparative analysis on CCE between the inner sprawling suburbs and outer suburbs was conducted. It was found that: (i) the increases in CCE are several times larger than the increases in urban size, population, and economic developments; (ii) metro services reducing CCE near metro stations is not statistically significant, maybe because the proportions of car users near the metro stations are similar to the two cities' average levels, which is caused by their higher household income and the longer travel time using the metro; (iii) in Beijing, there are smallest CCE in the outer suburbs due to job-housing balances, short distance and large percentage of non-motorized mode uses while largest CCE in the inner sprawl suburbs due to car trips with long distance. These findings indicate that to cope with the rapidly increasing CCE, more attention should be paid to developing strong industry and real-estate simultaneously; the improvement in the feeder bus and public bicycle systems should also be reinforced to reduce the total travel time of metro users; and satellite cities with job-housing balance are greatly needed. The implications will benefit efforts to reduce CCE and mitigate global climate change, and they also provide empirical evidence and reference values for other global cities.

1. Introduction

Global warming, ice melting, and increasing sea levels are mainly caused by greenhouse gas (GHG) emissions produced by human beings (IPCC, 2007). CO_2 is of the most significance, and takes up about 65% of total GHG emissions (WMO, 2014). The transportation sector is a major emitter of CO_2 and currently contributes 20–25% of global CO_2 emissions, with its global share estimated to rise to 30–50% by 2050 (Brand et al., 2013). China, as the largest economy in the developing world, is now experiencing rapid economic growth, motorization and urbanization. Commuting is significant in Chinese cities, with commuting times concentrated and traffic frequently congested. As such, it is significant and necessary to reduce the commuting

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CO_2 emissions for the low carbon emission of the transportation development in Chinese cities and global climate change mitigations.

For transport CO_2 emission reduction, previous research studied the correlation between transport CO_2 emissions and socio-economic and urban form characteristics, and explored the spatial distribution of emissions in single cities (Ko et al., 2011; Brand and Boardman, 2008; Brand et al., 2013; Büchs and Schnepf, 2013; Brand and Preston, 2010; Susilo and Stead, 2009; Carlsson-Kanyama and Lindén, 1999; Yang et al., 2017; Wang et al., 2016). However, so far, there still lacks comparative analysis between cities. Comparative studies are necessary to understand the regularities in travel patterns, transport CO_2 emissions, and their spatial distributions, as well as their relationships with socio-economic and urban form characteristics after cities experience rapid growths. And, the findings from this kind of comparative case study can be helpful for fast growing cities to mitigate the increasing prevalence of transport CO_2 emissions. Besides this, existing studies on activity-based models have not considered the changing tendencies of travel behavior after the city rapidly sprawls and develops, and these models were not linked to transport CO_2 emissions (Henson et al., 2009; Rasouli and Timmermans, 2013). Therefore, to fill this gap in the literature, this paper will make a comparative case study on the above aspects in two typical sprawling Chinese cities: Beijing (a more developed city) and Xi'an (a rapidly developing city).

Further, there still exist different views on the benefits of rail transit on the mode choices and the transport environment (Litman, 2007, 2016; Zhu and Diao, 2016; Shen et al., 2016; Wachs, 1993; Kain, 1999; Winston and Maheshri, 2007; Lave, 1998; Guerra, 2014; Wang et al., 2013). Thus, in this study, we intend to explore the effects of rail transit on reducing commuting CO_2 emissions along the rail corridors in Beijing (with rapid and excellent metro developments) and Xi'an (in the beginning stages of metro developments).

In addition, there have been limited studies on the comparison of travel patterns and associated transport emissions between the inner suburbs and the outer suburbs/satellite cities in Chinese cities experiencing rapid suburbanization. Differences may exist in the rapidly developing cities due to differences in socio-economic, urban form or other factors. Hence, this paper will also make the above comparative analysis in the suburbs of Beijing, given its rapid suburbanization in recent decades.

The implications from this paper will not only benefit Chinese cities reducing their commuting CO_2 emissions in the process of the rapid economic growth, motorization, urbanization, and city cluster development, but will also provide empirical evidence and valuable references for other cities around the world.

2. Related work

2.1. Socio-economic characteristic and transport CO_2 emissions

Previous studies have found strong relationships between socio-economic characteristics and transport CO_2 emissions in single cities. middle-aged people emit more transport CO_2 emissions than those of other age groups (Ko et al., 2011; Brand and Boardman, 2008; Brand et al., 2013), high-income people produce more transport CO_2 emissions than those with low incomes (Ko et al., 2011; Büchs and Schnepf, 2013; Brand et al., 2013; Brand and Preston, 2010; Brand and Boardman, 2008; Susilo and Stead, 2009), households and individuals with car availability produce more transport CO_2 emissions than those without cars (Ko et al., 2011; Brand and Preston, 2010; Brand and Boardman, 2008; Brand et al., 2013), full-time employees emit more transport CO_2 emissions than those with part-time jobs (Carlsson-Kanyama and Lindén, 1999; Susilo and Stead, 2009; Ko et al., 2011; Brand et al., 2013), and persons with higher education qualifications emit more transport CO_2 emissions than those with lower education qualifications (Büchs and Schnepf, 2013). Besides this, work unit type is also an indicator of transport CO_2 emission. It was found that commuters working in the government in Xi'an, China (Yang et al., 2017) and in foreign companies in Bangalore, India (Wang et al., 2016) produced more transport CO_2 emissions than other work types considered.

2.2. Urban form, household Location, transport CO_2 emissions, and spatial distribution

In terms of urban forms and related transport CO_2 emissions, it was found that higher transport CO_2 emissions is associated with lower density and vice versa (Newman and Kenworthy, 1989; Frank et al., 2000; Norman et al., 2006; Makido et al., 2012; Hong and Shen, 2013), while lower transport CO_2 emissions were associated with mixed land use patterns (Guo et al., 2014). Notably, the effect of short distances from a household to a bus stop in reducing transport CO_2 emissions was mixed. Residents living near bus rapid transit corridors tend to produce less transport CO_2 emissions in Jinan of China (Guo et al., 2014), and the farther from the bus stop, the higher the commuting CO_2 emissions in Bangalore of India (Wang et al., 2016). However, in Xi'an, China, short distances from the household to the bus stop did not have statistically significant effects in reducing commuting CO_2 emissions (Yang et al., 2017).

For household locations and associated transport CO_2 emissions, previous studies' results showed that people located in the peri-urban areas emitted higher transport CO_2 emissions while people located in the city centers emitted lower emissions in France (Nicolas and David, 2009). Households in rural places were strongly associated with higher transport CO_2 emissions than urban households in the United Kingdom (Büchs and Schnepf, 2013). Household locations separated by ring roads was found to be a significant factor in commuting CO_2 emissions, with households located between the 2nd and 3rd ring roads associated with higher emissions (Yang et al., 2017; Wang et al., 2016).

The results of the spatial distribution of transport CO_2 emissions by zones in entire urban areas in Xi'an, China and Bangalore, India show that there exists higher commuting CO_2 emissions in the outer areas, the areas along the ring roads and radial roads, but lower emissions in the inner downtown areas. Further, as the straight-line distance from the household to the city center increases, the emissions also increase (Yang et al., 2017; Wang et al., 2016).

2.3. Activity-based analysis of travel behaviors and models

In the study by Ettema and Timmermans (1997), activity-based approaches were defined to "typically describe which activities people pursue, at what locations, at what times and how these activities are scheduled, given the locations and attributes of destinations, the state of the transportation network, aspects of the institutional context, and their personal and household characteristics". These have been a focus of transportation research for almost forty years and have gained considerable progress in model developments and applying these models to planning practice (Henson et al., 2009; Rasouli and Timmermans, 2013). However, there still exist opportunities for improvement in activity-based approaches, which mainly lie in spatial and temporal resolutions, specifying explicit cognitive-behavioral capabilities, reliability of land use and population information, improving activity schedule creation and better understanding of inter- and intra-household interactions (Henson et al., 2009). Further, there still exist several issues to be addressed in the future, including developing dynamic models of activity-travel demand, the integration of demand generation and its assignment to networks, expanding application domains beyond pure transportation (such as linked to the emission and health indicators), impact of smart phones and other information communications technology (ICT) on activity-travel decisions, the need for behavioral enrichments, and models of decision-making under uncertainty (Rasouli and Timmermans, 2013).

2.4. Competing opinions on rail transit

Many studies have discussed the advantages and disadvantages of rail transit, however, there still exists mixed perspectives on its effects on transportation more widely. Proponents of rail transit maintain that it increases transit ridership, reduces driving, and benefits social equity and environmental sustainability. high quality and grade-separated transit reduced urban traffic congestion in the U.S. (Litman, 2007, 2016), urban mass rapid transit (MRT) lines lowered the levels of car dependence and promoted more reliance on the MRT in Singapore (Zhu and Diao, 2016), and in the suburban areas in Shanghai, proximity to metro stations was found to have a significantly positive association with the choice of rail transit as the primary commuting mode (Shen et al., 2016). However, critics question rail transit's ability to generate ridership, reduce car use and be cost effective in low-density and automobile-oriented cities with smaller downtowns. In Los Angeles, although transportation policies have emphasized greater capital investment in rail transportation than in highways, and policies have attempted to discourage automobile usage through transportation demand management, these policies could only generate small shifts to public transport and only somewhat lowered dependence upon singly-occupied automobiles for work commuting (Wachs, 1993). Other issues include below-forecast ridership (Kain, 1999) and a high percentage of users from former bus passengers constituting 70–75% of rail transit ridership (Lave, 1998). Rail transit has had mixed and ambiguous effects in achieving environmental goals (Winston and Maheshri, 2007). In Mexico City, although metro use increases as lines extended to the suburbs, most of the increase came from people relying on informal transit, rather than cars. This shift increased government subsidies for the metro and had no apparent effect on road speeds, with the effects on car ownership and urban form considered modest as well (Guerra, 2014). The case of a developing country showed that when the metro services were introduced in Xi'an, China, there were many bus riders shifting to the metro, and the impact on easing traffic congestion by a single metro corridor was not significant (Wang et al., 2013).

2.5. Travel patterns and transport CO_2 emission in the suburbs

As suburbanization developed in western countries for many years, travel behavior and transport emissions in the suburbs have attracted a lot of attention. It was found that the over-reliance on automobiles and the lack of alternative forms of transportation, such as walking and bicycle riding, were the significant issues in suburban travel patterns in the U.S. metropolitan areas (Prevedouros and Schofer, 1991; Atash, 1994). Also, suburbs in Toronto, Cologne, and Adelaide had similar characteristics, with the highest GHG emissions located in Toronto suburbs because of high private automobile use (VandeWeghe and Kennedy, 2007). Suburbanization was found to increase car use and decrease public transport use, bicycle use and walking in Cologne (Scheiner and Holz-Rau, 2013). Car-dependent lifestyles exist in the suburbs of Adelaide but were ultimately considered unsustainable in the long run (Soltani and Allan, 2006). The case of Beijing showed that trip distance and car use for travel in the suburbs have increased greatly due to urban sprawl (Zhao, 2010) and that there are plenty of long-distance commuting to central urban areas (Zhao et al., 2010). However, the result from Wilson's study found that, in Halifax, Canada, the transport related GHG emissions produced by individuals living in the suburbs was not significant (Wilson et al., 2013). Apart from the above studies focusing on the suburban areas, research also focused on the transport patterns in rural places and exurbs showed that there exist higher transport related GHG emissions and longer drives in these areas than those in the inner cities and suburbs (Davis et al., 1994; Wilson et al., 2013).

2.6. This study on CCE

Previous studies about transport CO_2 emission and its factors mainly explored the relationships between socio-economic and urban form characteristics and transport CO_2 emissions, and explored the spatial distributions of the emissions in the single cities. Comparative analysis between cities has not been done before. For the fast growing cities in developing countries to cope with the increasing tendency of transport CO_2 emissions, it is important to know the changes in travel patterns, transport CO_2 emissions, and their spatial distributions, as well as their relationships with socio-economic and urban form characteristics after the city experiences rapid growth. Also, the existing studies on activity-based models do not consider the changing tendencies of travel behavior after a city rapidly sprawls and develops. In addition, these existing activity-based models were not linked to transport CO_2 emissions. Therefore, to fill this gap, this paper will make a comparative case study of two typical sprawling Chinese cities (Beijing and Xi'an) with different development levels.

Besides this, studies focused on mode choice behavior after the introduction of rail transit do not show the effect of the changes on transport CO_2 emissions. Further, there still exist ambiguous effects of rail transit on the environment. Thus, the impact of rail transit in reducing commuting CO_2 emissions will be analyzed in Beijing (with rapid and excellent metro developments) and Xi'an (in the beginning of the metro developments) in this study.

Finally, there is still a lack of comparative studies on travel patterns and associated transport emissions between inner sprawl suburbs and outer suburbs/satellite cities in developing countries. Compared with developed countries, there may be different tendencies due to different socio-economic, urban form or other factors. Thus, this paper will provide a comparative analysis in the suburbs of Beijing given its rapid suburbanization in recent decades.

3. Data collection

Household surveys were carried out in the main urban areas of Beijing and Xi'an for the data collection. The statistical method applied in the study to determine the sample size was from Meyer and Miller (2001), as shown in Eq. (1):

$$n = \frac{\left[Z_{1-(1/2)\alpha}\right]^2(1-p)}{r^2 p} \tag{1}$$

where r is the margin of error or precision, which is assumed to be 0.05 (assuming an estimate of the sample size within $\pm 5\%$ of the real value 95% of the time); p is the observed value of the proportion of commuting trips in the urban passenger transport system; $Z_{1-(1/2)\alpha}$ is the standard normal statistic corresponding to the $(1-\alpha)$ level.

Based on the calculation method of Eq. (1) and the proportions of the commuting trips in Beijing and Xi'an's urban passenger transport system (46.61% and 51.06%), it was calculated that the minimum 1760 and 1472 observations of commuting trips in Beijing and Xi'an, respectively, were needed to achieve the precision within $\pm 5\%$ ($r = 0.05$) of the real value 95% of the time ($\alpha = 0.05$). In Beijing, 1400 households and 1915 commuters were surveyed in total, and in Xi'an, a total of 1501 households and 2449 commuters were surveyed. The sample sizes of the two cities thus exceed the required minimum observations.

In Beijing, simple random sampling was implemented in each district and county in August of 2010. The survey was conducted by students from Renmin University of China. The students were well trained before the survey and conducted face-to-face enquiries within households. In Xi'an, simple random sampling was implemented in the traffic zones of Xi'an from November to December of 2012. On average, nine to ten households were surveyed in each traffic zone. The survey was done by graduate students from Chang'an University. The graduate students were well trained before the survey and conducted face-to-face enquiries within households.

The household survey included the commuting mode, commuting distance, household traffic vehicles' fuel consumption, household location, housing tenure, and commuter's work place. Besides this, socio-economic characteristics of the households and individuals were also surveyed, including household income, car availability, age, work unit type, and educational background.

The statistical results of the sampled households and individuals are shown in Table 1. We compared the characteristics of the sampled households and commuters with the overall population in Beijing and Xi'an in terms of commuters' work unit type, average household annual income, and the distributions of the samples using the data in the statistical yearbook of Beijing (BMBS, 2011) and Xi'an (XMBS, 2013), as well as the statistical bulletin of Beijing (BSIN, 2015). The maximum, minimum, and average errors between the surveyed and governmental statistical data in terms of households and commuters' characteristics are 11.72%, −14.46%, and 6.8%, respectively. It can be concluded that the samples well represent the overall population and the distributions of the samples accord with the realities in the two cities. As such, the survey data of the two cities are reliable for the study.

4. Methodology

4.1. Commuting CO_2 emission calculations

The most commonly used method for transport CO_2 emission calculations is proposed by the IPCC. The commuting CO_2 emissions were calculated as the emission factor (by mode, fuel type, and occupancy) multiplied by trip distance (IPCC, 1997), as shown in Eq. (2):

Table 1
Statistical results of the characteristics of the sampled households and commuters in Beijing and Xi'an.

	Levels	Beijing		Xi'an	
		N	(%)	N	(%)
Age	<35 years old	676	36.29%	971	49.74%
	35–55 years old	1062	57.00%	907	46.47%
	>55 years old	98	5.26%	64	3.28%
Work unit type	Government	175	9.39%	78	4.00%
	Public institution	538	28.88%	407	20.85%
	Foreign company	104	5.58%	26	1.33%
	Private company	587	31.51%	869	44.52%
	State-owned company	341	18.30%	314	16.09%
	Others	69	3.70%	213	10.91%
Education level	Middle school graduate	123	6.60%	149	7.63%
	Graduated from the high school or technical secondary school	367	19.70%	377	19.31%
	Graduated from college	381	20.45%	478	24.49%
	Bachelor's degree	774	41.55%	789	40.42%
	Master's degree	186	9.98%	125	6.40%
	Ph.D. degree	27	1.45%	20	1.02%
Household traffic vehicles	Household car availability	461	42.10%	507	40.89%
Household annual income	<US$2000	13	1.19%	3	0.24%
	US$2000–6000	143	13.06%	51	4.11%
	US$6000–10,000	212	19.36%	246	19.84%
	US$10,000–20,000	421	38.45%	778	62.74%
	US$20,000–40,000	262	23.93%	114	9.19%
	>US$40,000	41	3.74%	29	2.34%
Housing tenure	House owner occupied	897	79.59%	992	80.00%
	House is rented	230	20.41%	187	15.08%
Household location by ring roads	Inside the 1st Ring Rd.			76	6.13%
	1st – 2nd Ring Rd.			376	30.32%
	2nd – 3rd Ring Rd.			734	59.19%
	Outside the 3rd Ring Rd.			54	4.35%
	Inside the 2nd Ring Rd.	84	7.67%		
	2nd – 3rd Ring Rd.	198	18.08%		
	3rd – 4th Ring Rd.	181	16.53%		
	4th – 5th Ring Rd.	136	12.42%		
	5th – 6th Ring Rd.	247	22.56%		
	Outside the 6th Ring Rd.	203	18.54%		

$$C = EF \times L \tag{2}$$

where C is the CO_2 emission (kg/passenger/km); EF is the emission factor (by mode, fuel type, and occupancy); and L is the trip distance (km).

The commuting CO_2 emission factors are calculated by vehicle occupancy and Well-To-Wheel (WTW) CO_2 emission intensities of different fuel types drawn from the latest study on Chinese cities by Huo et al. (2012). The fuel consumed by vehicles is affected by factors such as driving speed, vehicle occupancy and so on (Wang et al., 2016), which can cause uncertainties in commuting CO_2 emission. Therefore, local data on the range of these values in Beijing and Xi'an were collected through surveys and related studies to calculate the range of the CO_2 emission factors by mode, vehicle type, fuel type, and occupancy, as shown in Table 2. This study used the average values of the commuting CO_2 emission factors to calculate the household and individual commuting CO_2 emissions in both cities.

4.2. Spatial distribution of commuting CO_2 emissions in urban areas

The method to reveal the spatial distribution of the commuting CO_2 emissions in urban areas is composed of two steps. Firstly, the Voronoi Diagram was used to divide the urban areas into continuous polygons, including only one sampled household according to the nearest neighbour rule (Aurenhammer, 1991). The reason we use the Voronoi Diagram lies in the fact that there are some zones without sampled households, and there will be no observations and commuting CO_2 emissions in these zones. After the Voronoi Diagram was applied in the urban areas of the two cities, each polygon included only one sampled household. Thus, we can attain the household and individual commuting CO_2 emissions within each polygon so that there are no breaks in emissions in the entire urban areas of the two cities. The second step is to let the polygons intersect with traffic zones, and thus the commuting CO_2 emissions at the zone level can be calculated by the area-weighted emissions of the intersections.

4.3. Commuting CO_2 emission model

Commuting CO_2 emission models of Beijing and Xi'an intend to explore the relationship between the commuting CO_2 emissions and the socio-economic and urban spatial factors. The distributions of the household and individual commuting

Table 2
Well-To-Wheel CO_2 emission factors by fuel type, traffic mode, vehicle type and occupancy in Beijing and Xi'an.

Mode	Fuel Type	WTW CO_2 Intensity (tons CO_2 eq./unit of fuel)[a]	Fuel consumptions Per 100 km[b]	Occupancy (passengers/ vehicle)[h]	WTW CO_2 emission factor (kg/passenger/km)	Average WTW CO_2 emission factor (kg/passenger/km)
Beijing						
Car	Gasoline	3.87/ton	8.58–10.45 (L)	1–3	0.081–0.295	0.188
Routine coach	Diesel	3.94/ton	39.12–42.38 (L)	20–50	0.027–0.072	0.050
Taxi	CNG	2.76/1000 m^3	8–10 (m^3)	2–5	0.044–0.138	0.091
Bus[i]	Diesel/CNG	3.94/ton 2.76/1000 m^3	39–42 (L)/52–58 (m^3)	80–100	0.013–0.020	0.017
Metro	Electricity	1.246/1000 kW h[j]	3400–3430 (kW h)[c]	1100–1600	0.026–0.039	0.033
Electric-bicycle[d]	Electricity	1.246/1000 kW h[j]	1.1–1.25 (kW h)[e]	1–2	0.007–0.016	0.012
Electric-motor[f]	Electricity	1.246/1000 kW h[j]	1.6–1.7 (kW h)[g]	1–2	0.010–0.021	0.016
Xi'an						
Car	Gasoline	3.87/ton	7.80–10.45 (L)	1–3	0.073–0.295	0.184
Routine coach	Diesel	3.94/ton	39.12–42.38 (L)	20–50	0.027–0.072	0.050
Taxi	CNG	2.76/1000 m^3	8–10 (m^3)	2–5	0.044–0.138	0.091
Bus	CNG	2.76/1000 m^3	52–58 (m^3)	60–100	0.014–0.027	0.021
Metro	Electricity	0.83/1000 kW h	3340–3350 (kW h)[c]	1100–1600	0.017–0.025	0.021
Electric-bicycle[d]	Electricity	0.83/1000 kW h	1.1–1.25 (kW h)[e]	1–2	0.005–0.010	0.008
Electric-motor[f]	Electricity	0.83/1000 kW h	1.6–1.7 (kW h)[g]	1–2	0.007–0.014	0.011

Note:
[a] Data was from Huo et al. (2012).
[b] Data was from Liu and Hou (2009), Huo et al. (2011), Zhang et al. (2014); and the fuel consumption considered the factor of vehicle speed in peak hours.
[c] Data was collected from the survey of Xi'an Metro Co., Ltd. and the survey data of the electricity consumption during the metro operations in Beijing.
[d] The highest speed of the electric-bicycle is 20 km/h.
[e] Data was from National Standard of the People's Republic of China, GB17761-1999: Electric bicycles - General technical requirements, issued by China State Bureau of Quality and Technical Supervision.
[f] The highest speed of the electric-motor is more than 20 km/h.
[g] Data was collected from the questionnaire surveys of the electric-motor users in Xi'an and Beijing.
[h] Data came from the Xi'an and Beijing Transport Development Annual Reports in 2012 and 2010 (XCTMCCU, 2012; BTRC, 2010) and the field surveys.
[i] Buses in Beijing were partly driven by diesel, and the CO_2 emission factor of buses in Beijing was weighted by the percentages of the diesel buses and CNG buses.
[j] Data was from the 'Guidelines for the Provincial Greenhouse Gas Inventory [2011]1041' issued by the National Development and Reform Commission in 2011.

CO_2 emissions in Beijing and Xi'an were analyzed. These distributions did not follow normal distributions. Therefore, the linear regression model with ordinary least squares estimation was not suitable for our calculations. Since the household and individual commuting CO_2 emissions are left censored at zero, Tobit models with Tobit maximum likelihood estimation were used, as shown in Eq. (3):

$$y_i = \begin{cases} x_i'\beta + \varepsilon_i & if \quad y_i^* = x_i'\beta + \varepsilon_i > 0, \\ 0 & if \quad y_i^* = x_i'\beta + \varepsilon_i \leq 0 \end{cases} i = 1, 2, \ldots, N \tag{3}$$

where y_i is the dependent variable; y_i^* is the latent variable; x_i' is a vector of independent variables; β is a vector of estimable parameters; N is the number of observations; and ε_i is a random term.

5. General descriptions of Beijing and Xi'an

The main industry areas, activity centers, road networks, and sampled households in Beijing and Xi'an are shown in Fig. 1. The size of the urban areas, the population, per capita GDP and main data of the transportation system in Beijing and Xi'an are shown in Table 3.

Beijing, the capital of China and located on the east of the country, is one of the most dynamic economic centers in China. The population and employment densities decrease from the inner areas to the outside regions. Inside the core area (approximately inside the 2nd Ring Rd.), the population density is about 23.9 thousand people/km^2. Beijing has been experiencing rapid urbanization, motorization and significant economic growth, and now is one of the first-tier cities in China. The city sprawls from the 2nd Ring Road to the 6th Ring Road with Tiananmen Square as the city center. The outer suburbs outside the 6th Ring Road were originally planned to be satellite cities. Financial Street has famous financial institutions, both domestic and international, and the central business district (CBD) boasts most of the global top 500 firms, located inside or near the central area of the city. Famous historical heritage buildings are also located in this area. At the outside area, there are high-tech industry development zones, including ZhongGuan Village, Electronic City, FengTai Park, and YiZhuang development zones. In Beijing, there exists strong industry development in the central area and northern part of the city. The gov-

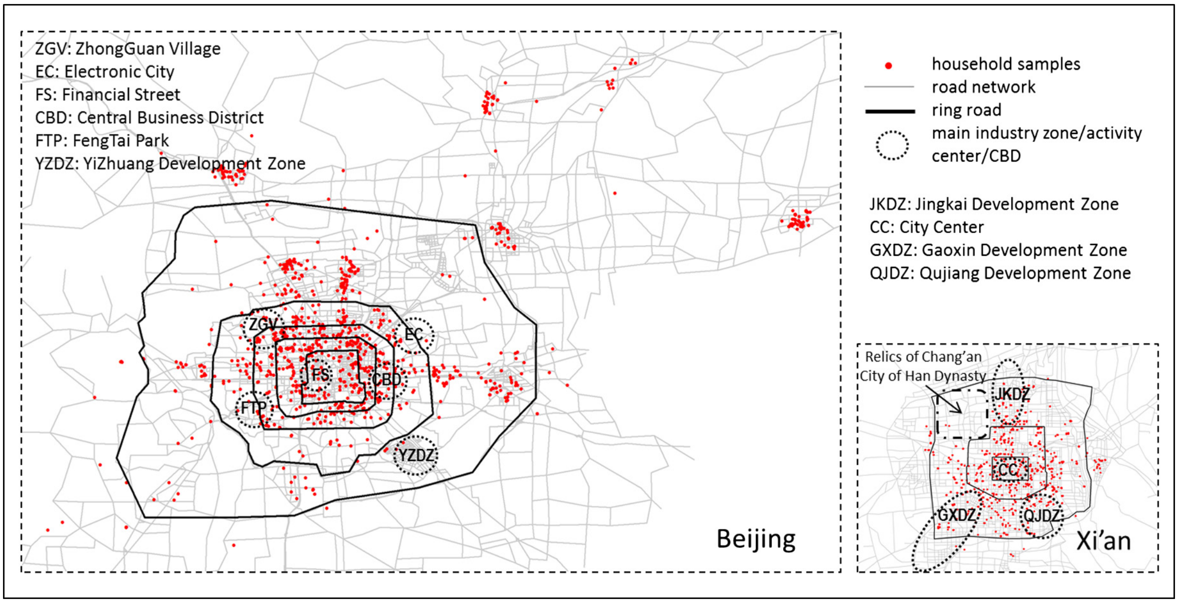


Fig. 1. Main industry zones/activity centers/CBD, road network, and the sampled households in Beijing and Xi'an.

Table 3
Areas by ring road, population, per capita GDP, and main transportation data in Beijing and Xi'an.

	Areas by ring road (RR) (km^2)								Urban built-up area (km^2)
	1st RR	2nd RR	3rd RR	2nd RR	3rd RR	4th RR	5th RR	6th RR	
Beijing[a]				62.5	159.1	300.2	664.8	2325.8	1268
Xi'an	12.3	74.5	347.3						522
	Total Population (million)	Population in the main urban area (million)	Per capita GDP (US$)	Number of the cars (million)	Bus Route	Bus Vehicle	Bus Lanes (km)	Metro Line[b]	Metro Line[b] (km)
Beijing	21.7	12.8	11218	3.9	713	21548	294	9 lines	228
Xi'an	8.6	4.5	8140	1	242	7695	200	1 line	20.5

Note:
[a] The data in Beijing and Xi'an refer to the years of 2010 and 2012, respectively.
[b] The metro data in Beijing and Xi'an refer to the time of the household surveys.

ernment in Beijing has paid a lot of attention to the transit development and transit priorities, and thus the bus and metro services in the city are of high quality compared to others in the developing world.

Xi'an city's urban development is similar to Beijing's and it is now rapidly growing with significant urbanization, motorization and economic growth. Xi'an is a second-tier city in the western part of China. The population and employment densities also decrease from the inner city to the outside areas. Inside the 1st Ring Road of the core area, the population density is about 36.8 thousand people/km^2. The city sprawls from the 1st Ring Road to the 3rd Ring Road with the Bell Tower as the city center. Inside the 1st Ring Road lies the city center and commercial center, with land developments controlled given the prevalence of historic heritage buildings. Outside the 2nd Ring Road, there are high-tech industry development zones and cultural tourism development zones. Jingkai, Gaoxin, and Qujiang are the three main areas of this nature. There exists strong industry development in the central area and southern part of the city. The government in Xi'an has also paid great attention to transit development and transit priorities.

6. Commuting mode share and distance

We can see from Fig. 2(a) and (b), in both cities, the average commuting distance of the metro is the longest (16.12 km in Beijing and 7.09 km in Xi'an), and the second longest is the routine coach (11.99 km in Beijing and 5.88 km in Xi'an). The

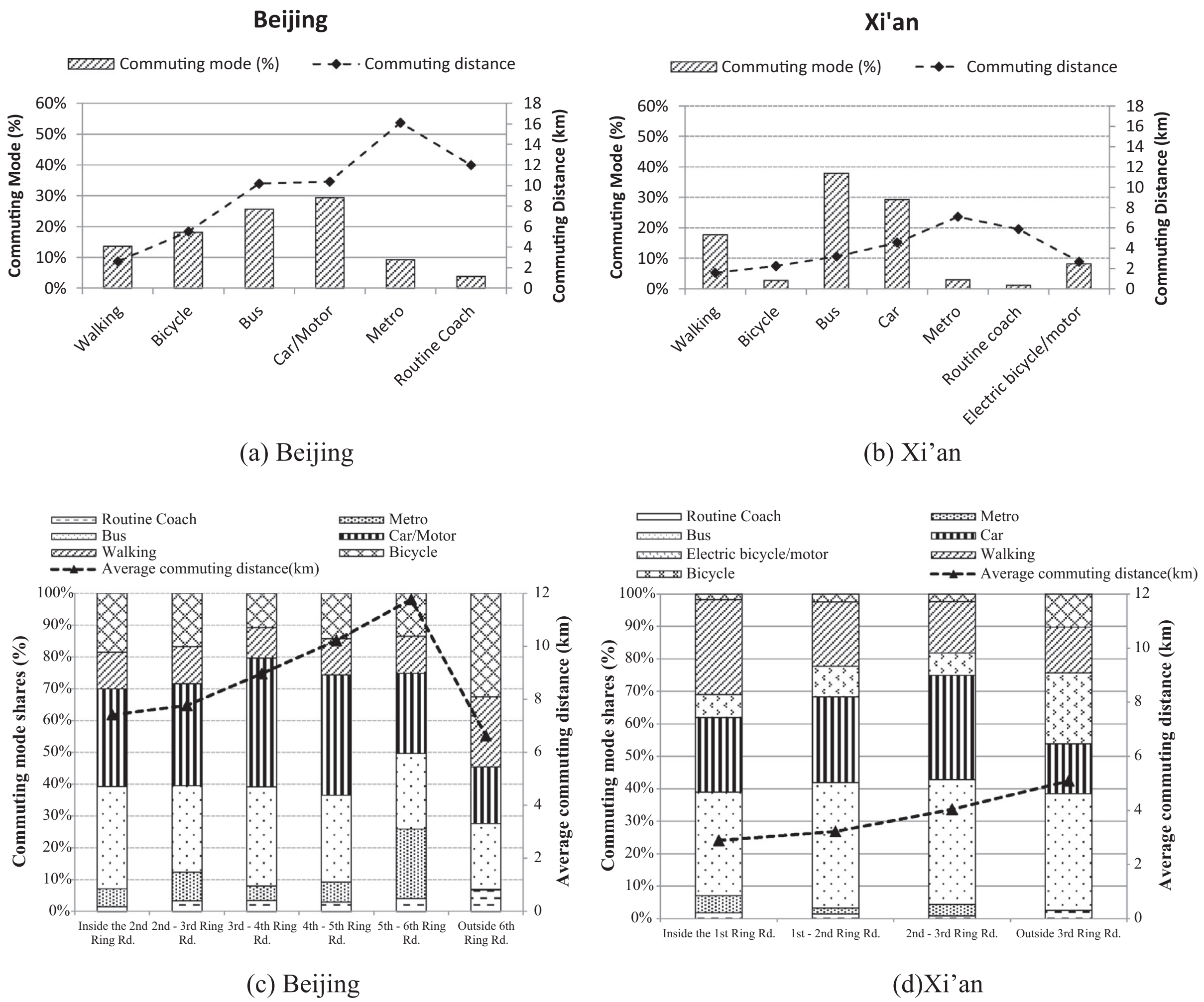


Fig. 2. Commuting mode share and distance in Beijing and Xi'an.

third is the car (10.39 km in Beijing and 4.56 km in Xi'an) and the fourth is the bus (10.19 km in Beijing and 3.17 km in Xi'an). There also exist differences between the two cities. Firstly, no matter what kind of traffic, there are much longer commuting distances in Beijing than in Xi'an, with the average distance in Beijing (9 km) being 2.38 times that of Xi'an (3.77 km). Secondly, in Beijing, the extent of car mode use is more than bus mode use, while in Xi'an, the extent of bus mode use outweighs car mode use. Further, the extent of walking in Beijing is less than in Xi'an. Thirdly, for the metro mode use, this is more prevalent in Beijing than in Xi'an. This can be attributed to the much longer metro network in Beijing, providing more metro services and covering more activity centers.

From Fig. 2(c) and (d), we found that: (i) commuting distances increase as commuters locate far from the city center inside the 6th Ring Rd. in the main urban areas of Beijing and Xi'an. Also, the percentage of car mode use increased inside the central urban areas of Beijing and inside the 3rd Ring Rd. in the main urban area of Xi'an, while there is a decreasing percentage of bus mode use in Beijing and decreasing percentage of walking mode use in Xi'an; (ii) there exists a larger percentage of car mode use and much longer commuting distances inside the main urban areas of Beijing than those in Xi'an; (iii) in the area between the 5th-6th Ring Rd. in Beijing, the commuting distance is the longest and it has the largest percentage of metro mode use; (iv) the shortest commuting distance, the smallest percentage of car mode use and the largest percentage of non-motorized mode uses was found in the outer suburbs of Beijing, which is located outside the 6th Ring Road, while continuously increasing commuting distances were found in the suburbs outside the 3rd Ring Road of Xi'an.

The results show that under the context of current transit priority policies and the strong rail transit service in Beijing, there still exists increasing use of cars and decreasing use of buses. Furthermore, as the city continues to sprawl, commuting distances will continue to quickly increase. These tendencies will be unsustainable for urban and transportation development in the future, amidst rapidly growing Chinese cities.

7. Commuting CO_2 emissions

7.1. Commuting CO_2 emissions by percentile of the population

Fig. 3 shows the commuting CO_2 emissions by percentile of the population in the two cities, and Table 4 shows the descriptive statistics of the commuting CO_2 emissions.

Similarly, in both cities, there exists a ‘70-20’ emission rule. The top 20% of the high emitters produce 70% of total emissions in both Beijing and Xi’an. This ‘70-20’ emission rule is typical for Chinese cities and differs from the ‘60-20’ emission rule in the United Kingdom (Brand and Preston, 2010; Susilo and Stead, 2009), indicating that the transport CO_2 emissions from the high emitters in Chinese cities contribute more to the total emissions in comparison.

Meanwhile, the average and total levels of individual and household commuting CO_2 emissions in Beijing are much larger than those in Xi’an, about 2.51 and 6.16 times larger than those in Xi’an, respectively, and there exist much larger differences in commuting CO_2 emissions among the population in Beijing compared to Xi’an. That is, the standard deviations of the individual and household commuting CO_2 emissions in Beijing are about 2.4 and 2.6 times those in Xi’an, respectively. The larger gaps in emissions among the population in Beijing are due to the much larger emissions produced by the high emitters.

7.2. Commuting CO_2 emissions by mode and percentile of the population

Fig. 4 shows the commuting CO_2 emissions by mode and percentile of the population in the two cities. We find that, in both cities, the commuting CO_2 emissions produced by cars contribute much more to the total emissions, followed by routine coaches and the metro, and then buses. Note that the commuting CO_2 emissions produced by routine coaches, the metro, and buses in Beijing are slightly higher than those in Xi’an; however, the commuting CO_2 emissions produced by cars in Beijing are much larger than those in Xi’an, with commuting CO_2 emissions from cars of the top 10th percentile in Beijing about 2.31 times more than those in Xi’an. This is related to the much longer distances for car trips in Beijing (10.39 km on average) compared to Xi’an (4.56 km on average). The results indicate that there will be a quickly increasing tendency of commuting CO_2 emissions produced by cars as the city grows, which will contribute significantly to urban transport CO_2 emissions.

7.3. Spatial distributions of commuting CO_2 emission

From Fig. 5(a) and (b), we can see that: (i) there exists increasing commuting CO_2 emissions by all modes of transport as the distance from the household to the city center increases inside the main urban areas of Beijing, and among them, the

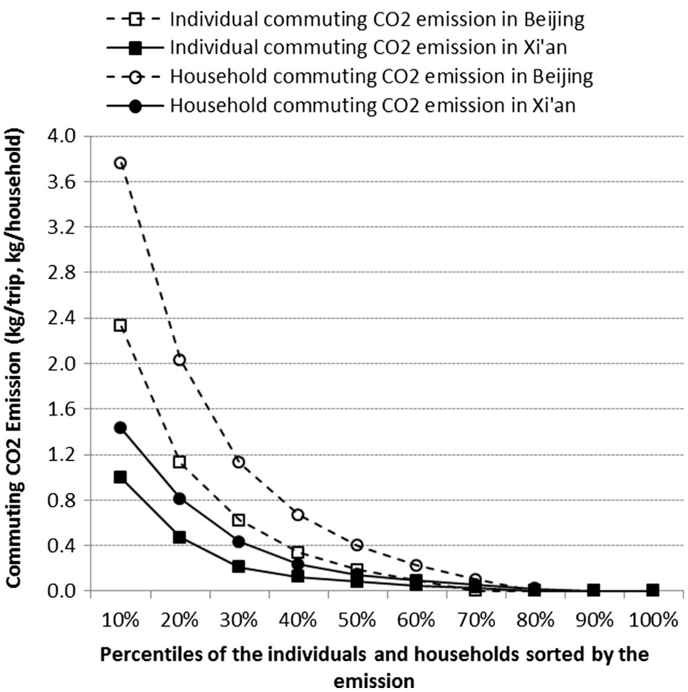


Fig. 3. Commuting CO_2 emissions by percentile of the population in Beijing and Xi’an.

Table 4
Descriptive statistics of the commuting CO_2 emissions in Beijing and Xi'an.

	Beijing		Xi'an	
	Individual (kg/trip)	Household (kg/household)	Individual (kg/trip)	Household (kg/household)
Min.	0.00	0.00	0.00	0.00
Max.	5.64	9.02	2.33	3.96
Avg.	0.68	1.16	0.28	0.45
Percentile of 25%	0.00	0.04	0.02	0.04
Percentile of 50%	0.18	0.40	0.08	0.14
Percentile of 75%	0.77	1.50	0.31	0.58
Variance	1.17	2.89	0.20	0.42
Standard Deviation	1.08	1.70	0.45	0.65

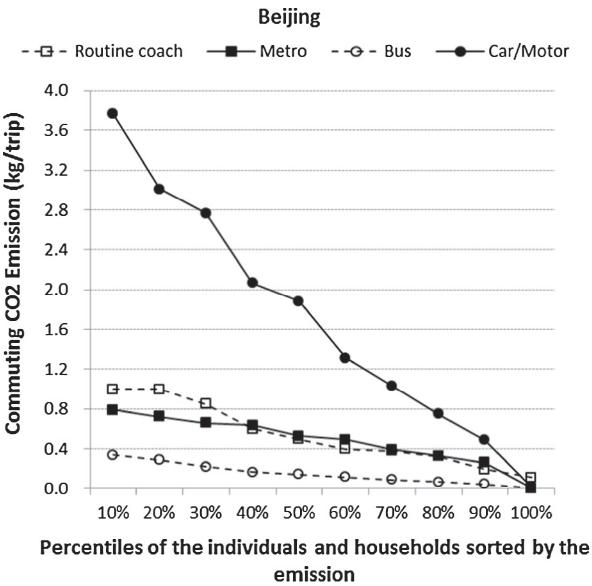
increase of the emission from cars is the most significant; (ii) there exists rapid increasing commuting CO_2 emissions from cars as the distance from households to the city center increases in Xi'an; (iii) the smallest commuting CO_2 emissions from cars was found in the outer suburbs of Beijing outside the main urban areas, while outside the main urban areas in Xi'an, the largest emissions from cars were found, which indicates an unsustainable tendency of urban sprawl.

Figs. 6 and 7 show the spatial distributions of the average household/individual commuting CO_2 emissions by zones in Beijing and Xi'an. The darker colour indicates a higher emission.

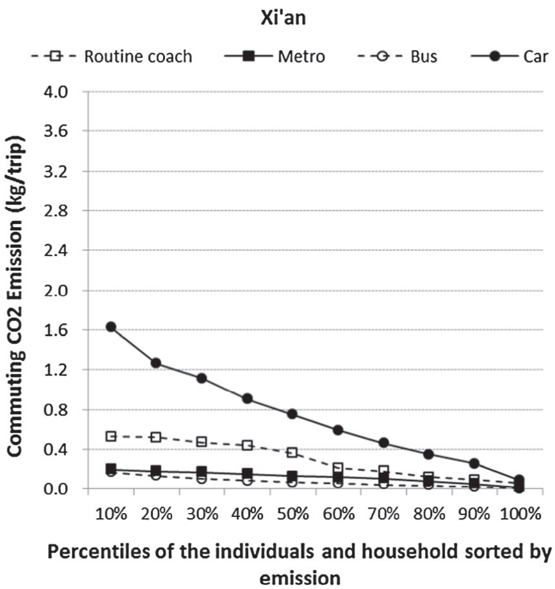
It was found that in the main urban areas of both cities, as the distance from the household to the city center increased, there was increasing household/individual commuting CO_2 emissions, and commuters located in the outer areas produced more emissions. Also, we can see that there were higher emissions along the ring roads and radial roads in both cities. In addition, the household/individual commuting CO_2 emissions have a reverse relationship with the populations and employment densities in both cities. In Beijing, there was less emissions outside the 6th Ring Rd. in the outer suburbs.

These findings indicate that the spatial distribution of the commuting CO_2 emissions will not change after the city experiences rapid growth under monocentric patterns. The outer areas and the areas along the ring roads and radial roads will always be associated with much larger emissions, mostly caused by long distance car trips.

In addition, Figs. 6 and 7 show that the household/individual commuting CO_2 emissions along the metro lines in Beijing and Xi'an are not noticeable lower than those in other areas. The effects of the metro service in reducing commuting CO_2 emissions in Beijing and Xi'an need to be further examined through statistical methods, which are shown in the next section.



(a) Beijing



(b) Xi'an

Fig. 4. Commuting CO_2 emissions by mode and percentile of the population in Beijing and Xi'an.

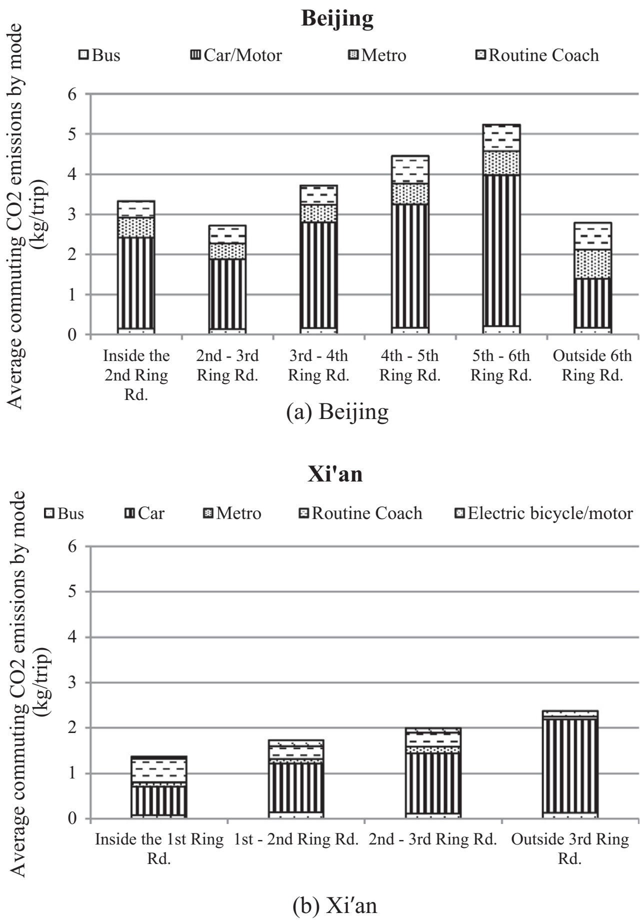


Fig. 5. Commuting CO_2 emissions by mode and ring roads in Beijing and Xi'an.

8. Model results for commuting CO_2 emissions

In the Tobit model for household commuting CO_2 emissions, the dependent variable is household commuting CO_2 emissions and the potential independent variables were household car availability, household annual income, household tenure, household location separated by the ring roads, straight-line distance from the household to the city center, and whether there are bus stops and metro stations around the household location within 500 meters. In the Tobit model for individual commuting CO_2 emissions, the dependent variable is individual commuting CO_2 emissions and the potential independent variables were household car availability, commuter's age, work unit type, education background, household location separated by ring roads, straight-line distance from the household to the city center, and whether there are bus stops and metro stations around the household location within 500 m. In the Tobit models of the pooled data of Beijing and Xi'an, since there exist differences in the ring roads between Beijing and Xi'an, and the areas inside the 4th Ring Rd. in Beijing (300.2 km^2) is roughly equal to the area inside the 3rd Ring Rd. in Xi'an (347.3 km^2), the variable of household location between the 2nd and 3rd Ring Rd. and the variable of household location between the 3rd and 4th Ring Rd. in Beijing are combined. We name this variable as 'household location between the 2nd and 4th Ring Rd'.

All the potential independent variables were considered in the modeling process, and insignificant independent variables were removed. The best Tobit models for household and individual commuting CO_2 emissions in Beijing and Xi'an were specified with all significant variables.

To quantify the uncertainty in the model parameters, the bootstrapping technique was applied to estimate the standard errors and confidence intervals of the parameters (Rasouli and Timmermans, 2012; Petrik et al., 2016; Efron and Tibshirani, 1993). Since the bootstrap replications should be more than 500 or 1000 times for a sound estimation of the confidence intervals, according to the suggestions from Efron and Tibshirani (1993), in this study we applied bootstrap replications 1000 times.

Table 5 shows the results of the Tobit models for commuting CO_2 emissions in Beijing and Xi'an using the original survey sample, and Table 6 shows the Tobit model results of the bootstrapping technique using 1000 bootstrapped samples. We can see from the tables that there is little difference in the parameter estimations and very small standard errors of the estimated parameters.

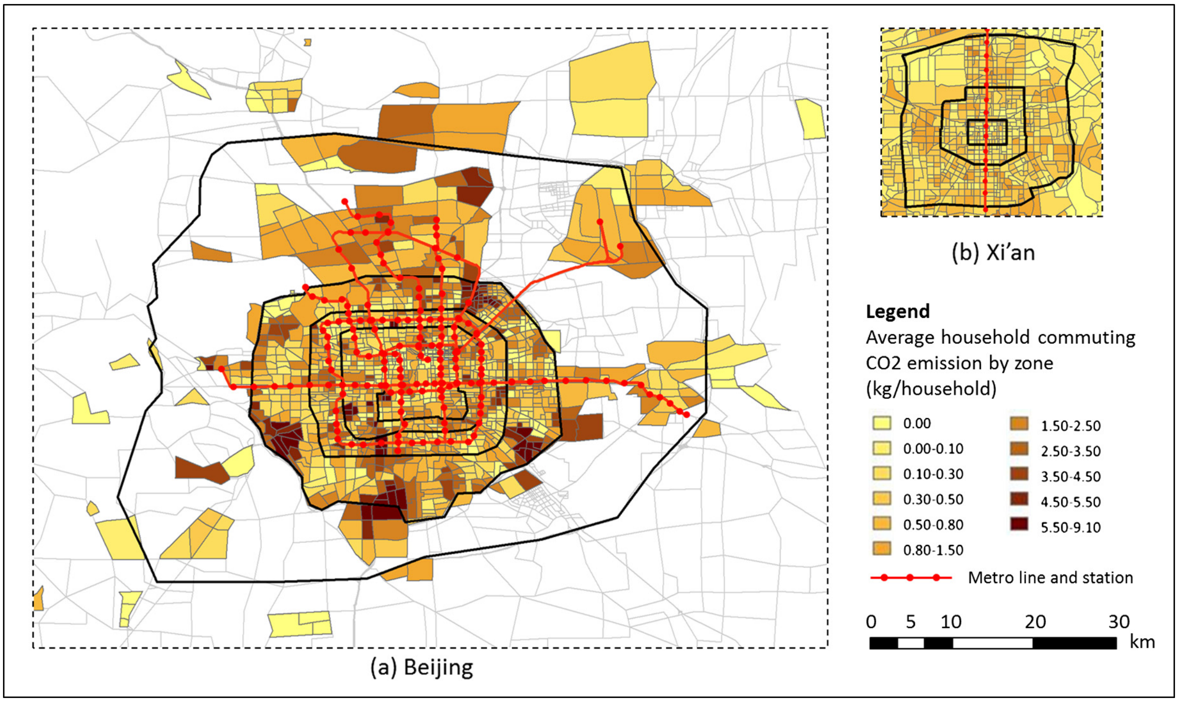


Fig. 6. Spatial distribution of household commuting CO_2 emissions by zones in Beijing and Xi'an.

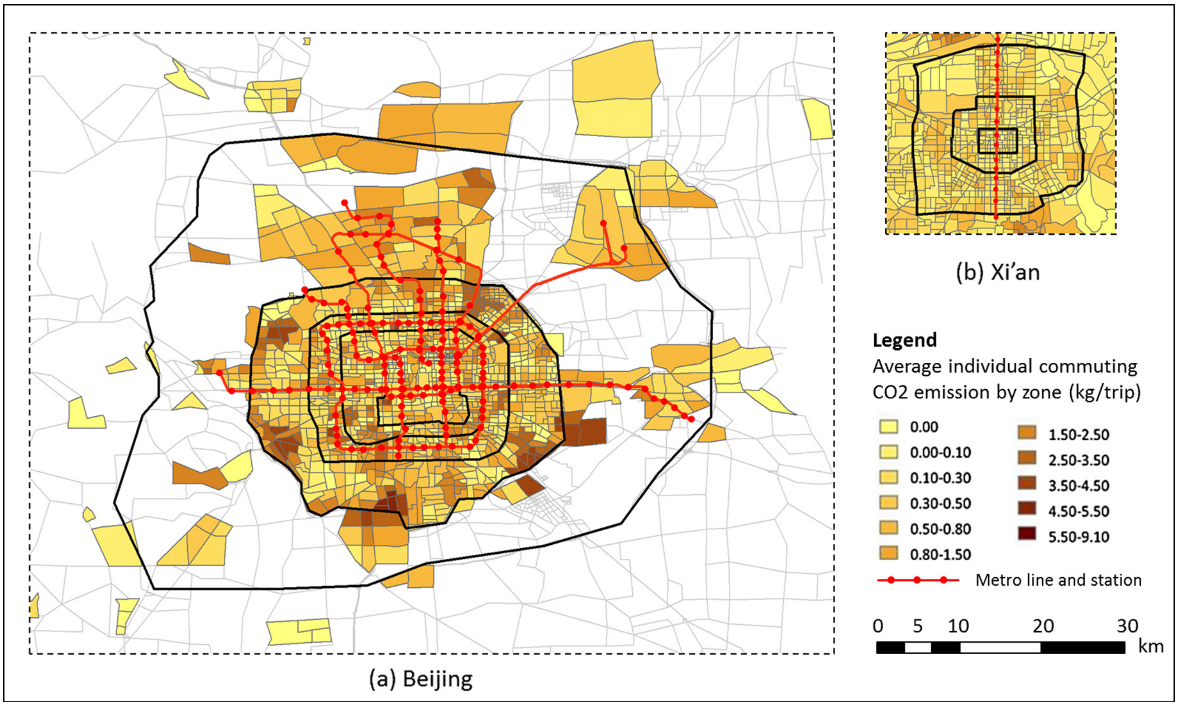


Fig. 7. Spatial distribution of individual commuting CO_2 emissions by zones in Beijing and Xi'an.

8.1. Comparison of the significant factors between the two cities

We can see from the model results that car availability, household location separated by ring roads, household income and commuters' work unit type are significant factors in determining commuting CO_2 emissions in both cities. The common characteristics in both cities are that commuters with car availability, higher household income, and those located in the

Table 5
Tobit models for commuting CO_2 emissions in Beijing and Xi'an.

Independent variables	Household models (kg/household trips)			Individual models (kg/trip)		
	Beijing	Xi'an	Pooled Data	Beijing	Xi'an	Pooled Data
Car availability	1.685(0.000)	0.919(0.000)	1.300(0.000)	1.154(0.000)	0.601(0.000)	0.964(0.000)
Household location by ring roads						
Inside the 1st Ring Rd.		−0.237(0.002)			−0.107(0.004)	
1st – 2nd Ring Rd.		−0.213(0.000)			−0.079(0.000)	
2nd – 3rd Ring Rd.		−0.109(0.077)				
Inside the 2nd Ring Rd.				−0.217(0.031)		
2nd – 3rd Ring Rd.	0.229(0.126)			−0.096(0.190)		
3rd – 4th Ring Rd.	0.582(0.000)			0.203(0.005)		
4th – 5th Ring Rd.	0.774(0.000)			0.218(0.020)		
5th – 6th Ring Rd.	0.818(0.000)			0.266(0.000)		
Inside the 2nd Ring Rd.			−0.346(0.000)			−0.262(0.000)
2nd – 3rd/4th Ring Rd.			−0.203(0.000)			−0.147(0.000)
Household annual income						
US$2,000–6000	−0.967(0.000)		−0.566(0.000)			
US$6,000–10,000	−0.722(0.000)	0.139(0.015)	−0.187(0.000)			
US$10,000–20,000	−0.300(0.010)	0.142(0.017)				
US$20,000–40,000	0.345(0.034)	0.201(0.024)	0.567(0.000)			
> US$40,000	0.737(0.077)	0.434(0.009)	0.857(0.000)			
Work unit type of commuter						
Government					0.112(0.068)	
Foreign enterprise				0.207(0.077)		0.240(0.009)
Public institution				−0.429(0.000)		−0.207(0.000)
If the city is Beijing			0.453(0.000)			0.180(0.000)
F	53.67	100.83	124.02	65.66	184.59	164.93
Prob > F	0.00	0.00	0.00	0.00	0.00	0.00
Log pseudolikelihood	−1711.69	−992.39	−3355.74	−2333.71	−993.68	−4139.11
Observations	1049	1240	2335	1746	1694	3508

Note: The numbers in the brackets refer to the *p* values.

Table 6
Tobit models for commuting CO_2 emissions in Beijing and Xi'an by bootstrapping.

Independent Variables	Household Models for 1000 Bootstrap Samples (kg/household trips)			Individual Models for 1000 Bootstrap Samples (kg/trip)		
	Beijing	Xi'an	Pooled Data	Beijing	Xi'an	Pooled Data
Car availability	1.685(0.118)	0.919(0.038)	1.300(0.056)	1.154(0.063)	0.601(0.023)	0.964(0.035)
Household location by ring roads						
Inside the 1st Ring Rd.		−0.237(0.081)			−0.108(0.038)	
1st – 2nd Ring Rd.		−0.214(0.063)			−0.079(0.019)	
2nd – 3rd Ring Rd.		−0.109(0.064)				
Inside the 2nd Ring Rd.				−0.218(0.097)		
2nd – 3rd Ring Rd.	0.229(0.140)			−0.096(0.073)		
3rd – 4th Ring Rd.	0.582(0.145)			0.203(0.713)		
4th – 5th Ring Rd.	0.774(0.191)			0.218(0.097)		
5th – 6th Ring Rd.	0.818(0.145)			0.266(0.063)		
Inside the 2nd Ring Rd.			−0.346(0.046)			−0.262(0.031)
2nd – 3rd/4th Ring Rd.			−0.203(0.045)			−0.147(0.264)
Household annual income						
US$2,000–6000	−0.968(0.140)		−0.566(0.091)			
US$6,000–10,000	−0.723(0.139)	0.139(0.058)	−0.187(0.056)			
US$10,000–20,000	−0.300(0.110)	0.142(0.061)				
US$20,000–40,000	0.345(0.159)	0.201(0.092)	0.567(0.094)			
>US$40,000	0.737(0.415)	0.434(0.179)	0.857(0.246)			
Work unit type of commuter						
Government					0.112(0.062)	
Foreign enterprise				0.207(0.112)		0.240(0.094)
Public institution				−0.429(0.066)		−0.207(0.038)
If the city is Beijing			0.453(0.046)			0.180(0.256)
Wald χ^2	532.61	817.04	988.89	533.79	746.09	1029.10
Prob > χ^2	0.00	0.00	0.00	0.00	0.00	0.00
Log pseudolikelihood	−1711.82	−992.72	−3355.74	−2334.14	−994.45	−4139.11
Observations	1049	1240	2335	1746	1694	3508

Note: The numbers in the brackets refer to the estimated parameters' standard errors by bootstrapping.

outer regions of the main urban areas produce more emissions; however, commuters with lower household income and those located in the inner regions of the main urban areas produce smaller emissions.

In terms of differences between the two cities, commuters working in foreign companies produce larger emissions in Beijing, while in Xi'an, commuters working for the government produce larger emissions. This can be explained by the higher percentage of car availability among commuters working in foreign companies in Beijing and for the government in Xi'an. The percentage of car availability among commuters working in foreign companies in Beijing is 51.9%, while the average city level is 44%. Also, in Xi'an, the percentage of car availability among commuters who work for government in Xi'an is 51.3%, while the average city level is 40.3%. Besides this, commuters working in public institutions in Beijing produce smaller emissions, while in Xi'an, this variable is not statistically significant. The smaller emissions produced by the commuters working in public institutions in Beijing correspond with their shorter commuting distances (7.7 km) compared to the city's average level (12 km in Beijing).

Furthermore, we can find that when there is increased car availability, increased distance to the city centers, and increased household incomes, emissions in Beijing rise more sharply than in Xi'an. The effect of car availability on increasing household and individual emissions in Beijing is about 2 times that of those in Xi'an. As the distance to the city center increases, the emissions of the households located in the outer areas increase by 0.128 kg in Xi'an, while in Beijing, this number amounts to 0.589 kg, which is about 4.6 times that of Xi'an. When household annual income increases from US$6000–10,000 to more than US$40,000 in Xi'an, the household emission increases by 0.295 kg. However in Beijing, the household emission increases by 1.459 kg, which is about 4.9 times that of Xi'an. These results indicate that there will be greater increase in transport CO_2 emissions from high emitters after a city experiences rapid growth in urban sprawl and economic activity.

The coefficients of household location separated by the ring roads within the 6th Ring Rd. in Beijing are almost all positive, which means that the commuters outside the 6th Ring Rd. in Beijing produce much smaller emissions. This can be attributed to the stronger job-housing balance in this area (indicated in the analysis of the next section). However, in Xi'an, we find the opposite effect. The coefficients of household location separated by the ring roads within the 3rd Ring Rd. in Xi'an are all negative, which means that the commuters outside the 3rd Ring Rd. in Xi'an produce the largest emissions. This indicates that Xi'an is under an unsustainable sprawling condition. Most of the urban commuters outside the 3rd Ring Rd. in Xi'an work in the inner parts of the city and endure longer commuting distances (only 32.8% of the commuters work locally).

In the Tobit models of the pooled data of Beijing and Xi'an, we found the same significant factors contributing to commuting CO_2 emissions as the model results of each city (car availability, household income, and household location separated by ring roads). The model results of the pooled data also show that commuters working in public institutions produced smaller emissions and commuters working in foreign companies produced larger emissions, which is in line with the individual model result of Beijing. Similarly, these results can be attributed to the higher percentage of car availability among commuters working in a foreign company (46.9%) than the average level of the two cities' data (42%), as well as the shorter distances for commuters working in public institutions (5.88 km) compared to the average level of the two cities' data (6.32 km). Besides this, when comparing the model results of the single cities with the pooled data model, we can find that there exist larger effects of high income on emissions compared with the effects of car availability. In addition, model results of the pooled data show that the household emissions in Beijing are 0.453 kg larger than those in Xi'an, and the individual emissions in Beijing are 0.180 kg larger than those in Xi'an.

8.2. The insignificant factor of the metro station around the household location

The variable of a metro station within 500 m of the household location is not statistically significant in both Beijing and Xi'an models for commuting CO_2 emissions.

In Beijing, the insignificance of this factor is related to the fact that the percentage of car use among commuters located near the metro station within 500 meters (29.88%) does not decrease, but actually increases slightly compared with the average level of the city (28.97%). That is, there are more commuters located near the metro station using cars for commuting (29.88%) than using the metro or bus for commuting (16.9% or 22.97%, respectively), as is shown in Table 7. This may be due to the reason that the average household income of the commuters located near metro stations in Beijing is about 1.14 times that of the city's average level, and the average household income of the commuters located near the metro sta-

Table 7
Commuting mode shares and average commuting distances for commuters located near the metro stations and the city levels in Beijing and Xi'an.

	Car	Metro	Bus	Routine coach	Walking	Bicycle	Electric bicycle/motor	Average commuting distance (km)
Commuters located near the metro station (within 500 m)								
Beijing	29.88%	16.93%	22.97%	3.63%	12.44%	14.16%	0.00%	9.44
Xi'an	22.83%	16.54%	29.13%	0.00%	22.83%	3.15%	5.51%	3.82
Average level of the city								
Beijing	28.97%	9.33%	25.88%	3.85%	13.67%	18.29%	0.00%	9.00
Xi'an	28.76%	3.06%	38.21%	1.14%	17.86%	2.70%	8.26%	3.77

tions still choosing cars for commuting is about 1.5 times that of the city's average level. Apart from the higher household income, longer commuting time of using the metro or bus is probably another reason. The statistical results show that in Beijing, the average commuting time of commuters located near the metro stations, who actually use the metro is longer (46.9 min) than using a car (32.2 min), and the average commuting time of using the metro at the city level (48.7 min) is also longer than using a car (30.9 min).

In Xi'an, the percentage of car use among the commuters located near the metro station within 500 meters (22.83%) decreases when compared with the city's average level (28.76%), as is shown in Table 7. Although there exist less commuters using cars along the metro line 2 corridor in Xi'an compared with the city's average level, the effect of the metro service in reducing commuting CO_2 emissions is not statistically significant in the models, indicating that the variable of a metro station being within 500 meters around the household location is not an important explanatory factor of commuting CO_2 emissions. This may be explained by the fact that commuters located near the metro station have lower household incomes, about 90% of the city's average level. Indeed, this metro line in Xi'an is located in the north-south axis of the city with many old neighborhoods of small apartments. Less proportion of the car users along the metro line 2 corridor in Xi'an may be also associated with the commuting time. The average commuting time of commuters located near the metro stations who actually use the metro (22.8 min) is slightly longer than the commuting time using cars (20.6 min), and the average commuting time using the metro at the city level (21.3 min) is also slightly longer than commuting by car (19.5 min).

Besides this, we can see from Table 7 that: (i) there exists a smaller percentage of bus users and larger percentage metro users near the metro stations compared with the two cities' average levels, which indicates that there is a shifting from bus to the metro in both cities; (ii) a slightly larger percentage of car users near the metro stations in Beijing reflect that metro services are not attractive to car users; (iii) the motorized mode share near the metro stations in Beijing (73.4%) is more than that at the city level (68%), indicating that there is higher mobility near metro stations.

9. Commuting patterns and CO_2 emissions in the suburbs of Beijing

The commuting patterns and CO_2 emissions in the suburbs located outside the 5th Ring Rd. in Beijing were analyzed, including the districts of FangShan, ChangPing, HuaiRou, ShunYi, PingGu, MiYun, DaXing, TianTongYuan, TongZhou, HuiLongGuan, and YiZhuang, which are shown in Fig. 8.

Fig. 9(a) shows that commuters located between the 5th and 6th Ring Rd. in the areas of TianTongYuan, TongZhou, DaXing, HuiLongGuan, YiZhuang in the inner sprawl suburbs produced much more emissions and had longer distances than the commuters located outside the 6th Ring Rd. in the outer suburbs. Fig. 9(b) shows that commuters located in the outer suburbs use more non-motorized traffic modes (walking and bicycle); however, commuters located in the inner sprawl suburbs tend to use cars, buses, and the metro for commuting. Fig. 9(c) shows that there exists more bus and metro services and

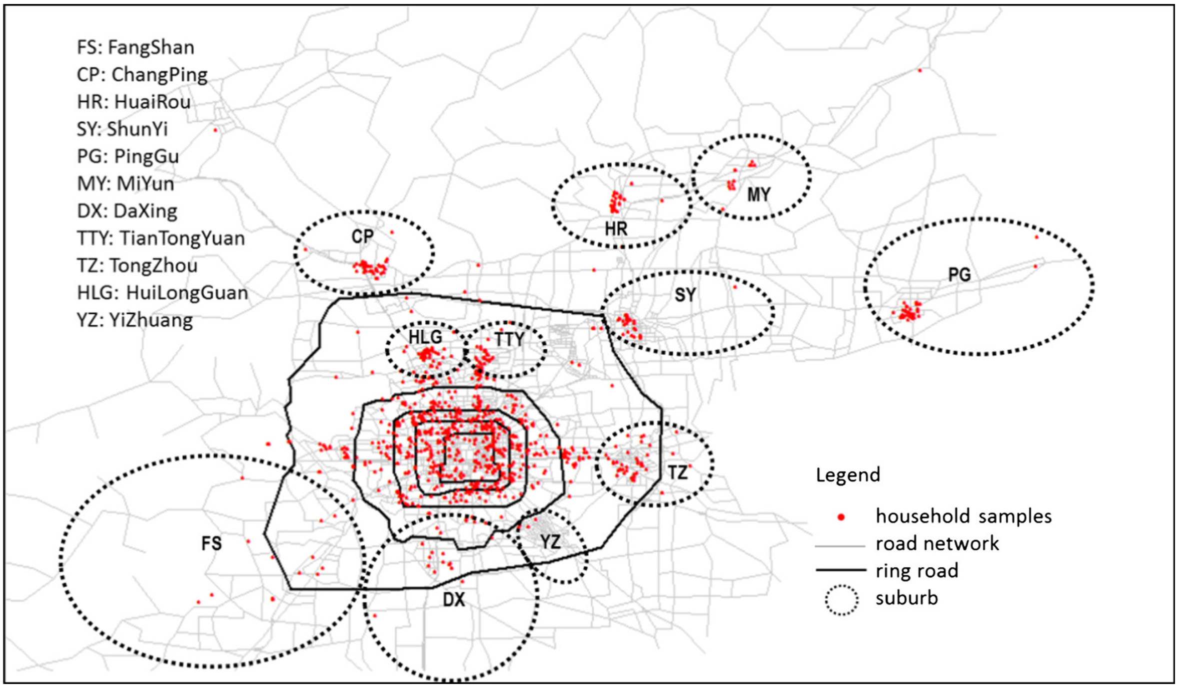
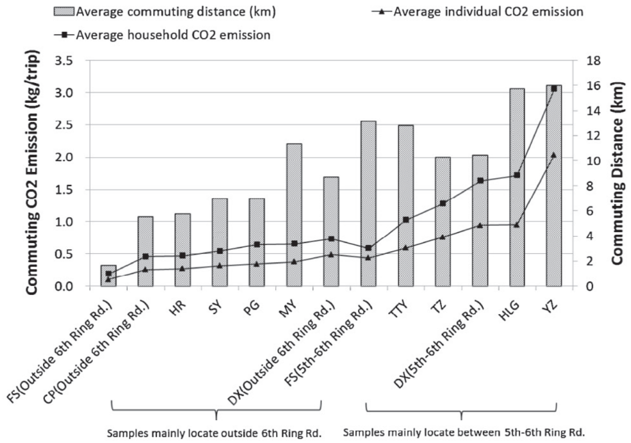
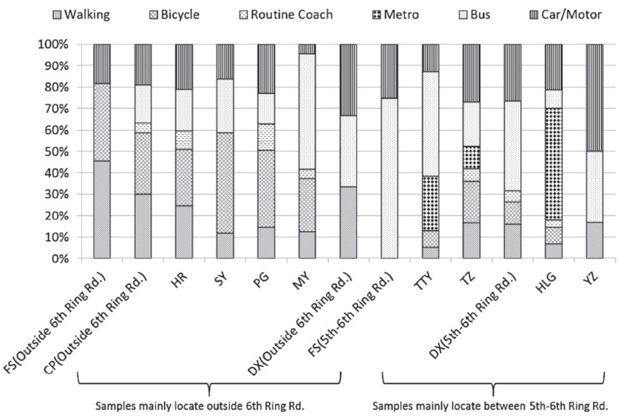


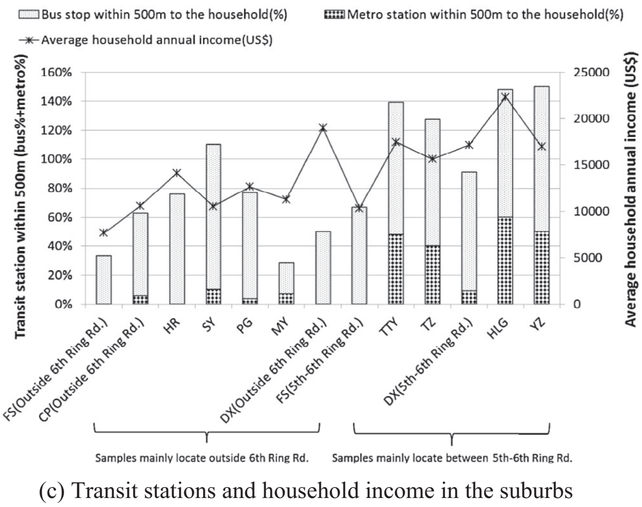
Fig. 8. Suburbs of Beijing.



(a) Commuting CO_2 emissions and distance in the suburbs



(b) Commuting mode shares in the suburbs



(c) Transit stations and household income in the suburbs

Fig. 9. Commuting patterns, CO_2 emissions, transit stations and household income in the suburbs of Beijing.

higher household incomes in the inner sprawl suburbs than in the outer suburbs. The statistical results of the samples also show that in the inner sprawl suburbs, there is much larger percentage of metro users (28.4%), a little larger bus users (24%), and smaller car users (22.2%) compared with the city's average levels.

These results indicate that, compared with the outer suburbs, and even though there are higher coverage rates of buses and metro stations and more bus and metro users in the inner sprawl suburbs, there are still much more commuting CO_2 emissions in these areas. This can be explained by the fact that car trips to the central urban areas, with longer distances, contribute much more to the total and average commuting CO_2 emissions in these areas. These areas have much more real-estate and have had less industry developments during the rapid process of the city's suburbanization and sprawl in recent decades, and more commuters are attracted to live in these areas because of affordable housing. Consequently, there exist a large number of commuters working outside their living suburbs (68%) and more connections with the central parts of the city. Coupled with higher household income and car availability and longer commuting distances, increased commuting CO_2 emissions inevitably occur in these areas.

However, cases in the outer suburbs are quite difference. There exist a large number of commuters who work locally (88.3%). The more walkers and bicycle users can be explained by the greater job-housing balance and short commuting trips (6.5 km in average) in these areas with self-contained developments.

The areas of inner sprawl suburbs in Chinese cities have good road infrastructure, much more real-estate and less industry developments, while the areas of the outer suburbs are mostly the originally planned satellite cities, which have been independent of the central urban areas for a long time.

The outer suburban travel patterns and associated transport CO_2 emissions are different from those in the developed countries. In the developed countries, commuters located in the suburban, rural or exurb areas mostly use cars for commuting, and they not only travel to the central urban areas, but also to other suburbs, and thus these areas are all associated with more commuting CO_2 emissions (Prevedouros and Schofer, 1991; Atash, 1994; Soltani and Allan, 2006; VandeWeghe and Kennedy, 2007; Scheiner and Holz-Rau, 2013). Low density, dispersed development patterns, and few public transit services are the main reasons why there is an over-reliance on cars in the suburban, rural or exurb areas in developed countries. While in Chinese cities, there exist few commuting trips among the suburbs and many trips from the inner sprawl suburbs to the central urban areas. In the outer suburbs or satellite cities with independent and self-contained developments, there exist much more local commuting trips and thus less commuting CO_2 emissions.

The links between the central urban areas, inner sprawl suburbs, and outer suburbs or satellite cities will become closer during the continuous urban sprawls, city clustering and rail transit development. Therefore, Chinese cities should avoid more real-estate developments and should keep a job-housing balance in the outer suburbs or satellite cities. Otherwise this will cause more separation in workplace and residence locations, leading to detrimental environmental impact.

10. Discussion and conclusion

In the context of transit priority policies and good rail transit services in the more developed Chinese cities, there still exists increasing use of cars, commuting distances, commuting CO_2 emissions, and few commuters opting for walking or bus alternatives. After experiencing urban sprawl and economic growth, these tendencies exist not only in the cities' outer areas but also in the inner areas. The spatial distribution of the commuting CO_2 emissions in the urban areas with monocentric patterns will not change after the city sprawls, and the outer areas, the areas along the ring roads and radial roads will always be associated with much more emissions. These characteristics and changing tendencies will be unsustainable in the long run, and thus deserve more attention from the rapidly growing Chinese cities.

The urban built-up areas, populations, and per capita GDP in Beijing are about 2.43, 2.52, and 1.38 times those of Xi'an. However, the total commuting CO_2 emissions in Beijing are about 6 times that of Xi'an, and the model results show that the effects of particular factors in explaining commuting CO_2 emissions are stronger in Beijing compared to Xi'an. For example, the increase of the emissions due to car availability, located in the outer areas, and higher household income in Beijing are about 2 times, 4.6 times, and 4.9 times of those in Xi'an, respectively. These results indicate that, compared with the developing city of Xi'an and under the context of transit priority policies and excellent transit and rail transit services in the more developed city of Beijing, there still exists about 2–6 times the commuting CO_2 emissions due to increasing commuting distances, household income and car availability. These tendencies represent challenges for rapidly growing Chinese cities in general.

In addition, from the results of Beijing and Xi'an models, the impact of the metro services in reducing the commuting CO_2 emissions near the metro station within 500 meters is not statistically significant. The reasons why those commuters located near the metro stations still prefer to use cars can perhaps be attributed to their higher incomes and shorter commuting times when using cars. Previous studies from Xi'an indicate that there are many bus riders shifting to metro after the introduction of the metro service (Wang et al., 2013). In this study, the statistical results of the mode shares, from both the data near the metro stations and the two cities, also show a ridership shift from the buses to the metros. These results reflect that metro services are not very attractive to car users with high income.

Furthermore, even though there is a much larger percentage of metro use (28.4%) and smaller percentage of car use (22.2%) in the inner sprawl suburbs between 5th-6th Ring Rd. in Beijing, these areas are still associated with the highest

commuting CO_2 emissions. The reasons lie in the much long commuting distance to the central urban areas, caused by the imbalance in job-housing locations and subsequent long-distance car trips.

Therefore, only providing rail transit is not enough to reduce the commuting CO_2 emissions in Chinese cities, especially in the outer areas. Fostering strong industries to reflect a job-housing balance in the suburbs and developing satellite cities instead of pie sprawling patterns are even more important. The case of the outer suburbs outside the 6th Ring Rd. of Beijing provides a good example. Apart from this, to reduce total travel time of using the rail transit, feeder bus and public bicycle systems should also be well developed.

The smallest commuting CO_2 emissions in Beijing's outer suburbs outside the 6th Ring Rd. are different from the larger emissions in the suburbs found in developed countries caused by suburb-center and suburb-suburb car trips. The outer suburbs in Beijing were originally planned to be satellite cities, which have been independent of the central urban areas and have more job-housing balance. With the process of rapid urban sprawl, city clustering and rail developments, there will be closer links among the outer suburbs/satellite cities, inner sprawl suburbs and central urban areas. The travel patterns in the outer suburbs or satellite cities may not be eco-friendly if there are more commuters attracted to work in the central urban areas or inner sprawl suburbs, which is on the alert to the rapid growing Chinese cities.

Looking to the future, with rapid motorization, urbanization, city clustering and rail development in most Chinese cities, there will be increased commuting distances and car ownership. Thus, to avoid the increase in commuting CO_2 emissions, car-use restrictions and transit priorities are the most important traffic demand management measures to be considered. It is only by these two measures, combined with strong industries in the suburbs and satellite cities, that can reduce the use of cars, commuting distances, and subsequently commuting CO_2 emissions.

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